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AUXILIARY LOOP FOR REMOVAL OF DECAY HEAT FROM A SPACE POWER REACTOR

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16. Abstract

An auxiliary radiator loop with sodium coolant was investigated as a possible means for removing decay heat from a proposed 2.17-megawatt space power reactor. Based on a selected set of operating conditions and assumptions, minimum areas were determined for the auxiliary loop heat exchanger and radiator. The minimum auxiliary heat exchanger surface area was determined to be 0.64 ft^2 (0.594 m^2), and the minimum auxiliary radiator surface area was 37.7 ft^2 (3.50 m^2). Based on these areas, the maximum temperature of the auxiliary radiator was about 1760° R (978 K). The flow rates and temperatures of sodium in the auxiliary loop were determined as a function of time after reactor shutdown for reactor operating times (before shutdown) of 1 year and 1 day. A significant conclusion from the preliminary study is that the size (and/or mass) of the auxiliary loop is relatively small.

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SUMMARY

An auxiliary loop using sodium as a coolant was investigated as a means for removing decay heat from a proposed 2.17-megawatt space power reactor. This loop consists of an auxiliary radiator, an auxiliary heat exchanger, a liquid sodium pump, and the necessary flow control valves and piping.

Based on a selected set of operating conditions and assumptions, minimum areas were determined for the auxiliary loop heat exchanger and radiator. The minimum auxiliary heat exchanger surface area required to transfer the decay heat from the reactor loop to the auxiliary loop was 0.64 ft^2 (0.0594 m^2). The minimum auxiliary radiator surface area required to reject the decay heat was 37.7 ft^2 (3.50 m^2). Based on these areas, the maximum temperature of the auxiliary radiator was 1760° R (978 K).

The configurations and minimum areas for the auxiliary loop heat exchanger and radiator were used to determine sodium flow rates and temperatures throughout the auxiliary loop as a function of time after reactor shutdown. The sodium flow rates and temperatures were determined for preshutdown reactor operating times of 1 year and 1 day.

It was concluded from this preliminary study that the size (and/or mass) of the auxiliary loop is relatively small.

INTRODUCTION

In the coming years, the electric power requirements for our nation's projected space programs will continue to increase. To meet these projected requirements, the Lewis Research Center has been participating in a technology program aimed at a relatively high-powered nuclear Brayton space powerplant.

The heat source being considered for the Brayton cycle space powerplant is a com-

pact, fast-spectrum nuclear reactor. The design thermal output of the reactor is 2.17 megawatts, and the design operating lifetime for the reactor and powerplant has been set at 50 000 hours.

An area of concern in the overall design of this powerplant is the removal of decay heat from the nuclear reactor following a system shutdown Although shutdowns are undesirable, particularly in a space power system, they must be considered in the system design. And provisions must be made for removing the reactor decay heat following a shutdown.

In this report, an auxiliary radiator loop with sodium coolant is investigated as a means for removing reactor decay heat. The objectives of this preliminary investigation are (1) to determine the size of an auxiliary radiator which will reject the decay heat and operate at an acceptable temperature level during the shutdown period, (2) to determine the size of an auxiliary heat exchanger which will transfer the decay heat from the reactor primary loop to the auxiliary radiator loop, and (3) to evaluate the sodium flow rates and temperatures in the auxiliary radiator loop as a function of time after shutdown.

An important consideration related to shutdown is the ability to restart the system and return it to the design operating level in a minimum amount of time. Based on this consideration, a mode of operation was chosen in which the reactor coolant temperatures were maintained at their respective design values during the period of shutdown.

DESCRIPTION OF POWERPLANT

A simplified diagram of a conceptual nuclear Brayton space powerplant is shown in figure 1. This system, in its present design configuration, has a single liquid-metal (lithium) primary loop, one or more complete inert-gas power conversion loops, and a main radiator loop for waste heat rejection.

The path of coolant flow in each of the three main loops is indicated in figure 1. During normal operation, the heat gained by the liquid lithium as it flows through the reactor is transferred to the gas power conversion loop by a heat-source heat exchanger. The heated inert gas is then expanded through a turbine. The work produced by the turbine drives a compressor and an electrical alternator. The exhaust from the turbine is cooled as it flows, first through the recuperator, and then through the waste heat exchanger.

Figure 2 shows a cutaway view of the reactor core design for this space power system. A detailed description of this reactor design is given in reference 1. The system design point operating conditions which are relevant to this study are listed in table I.

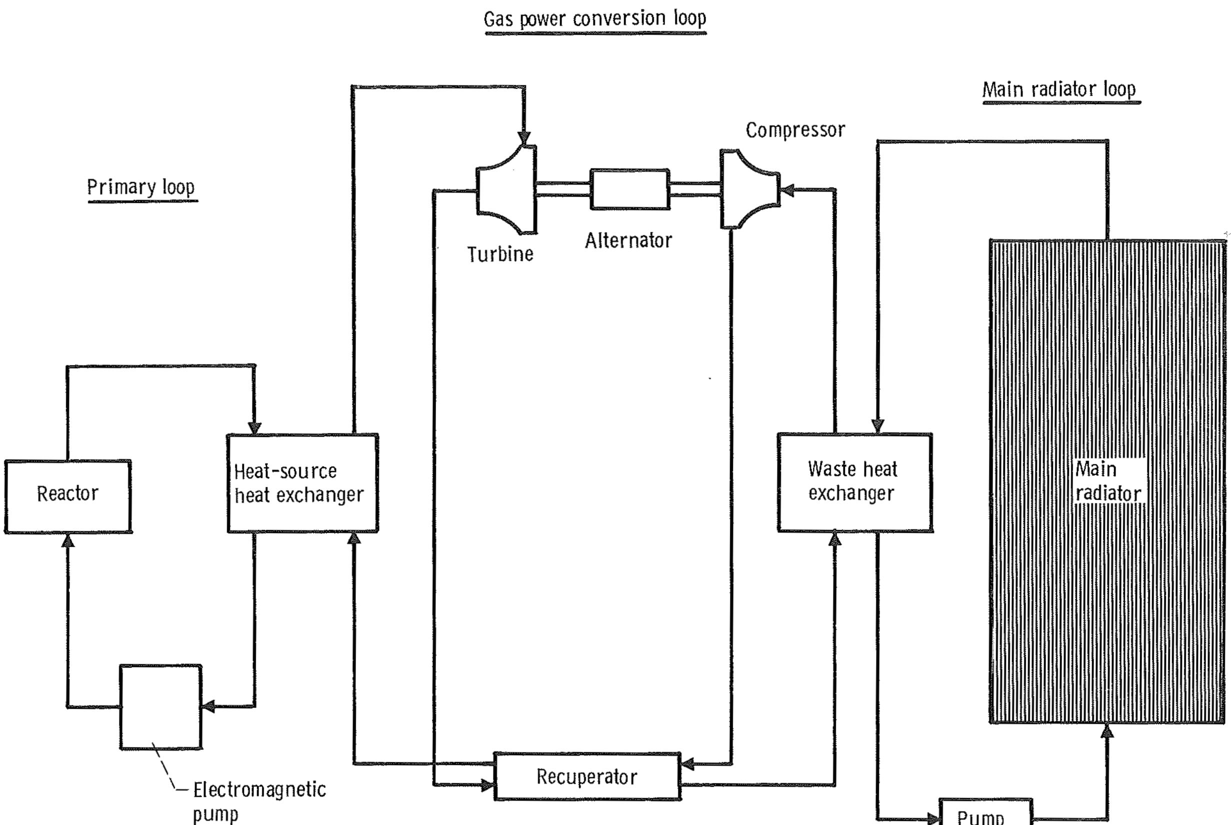

Figure 1. - Schematic diagram of a three-loop, recuperated, nuclear Brayton system.

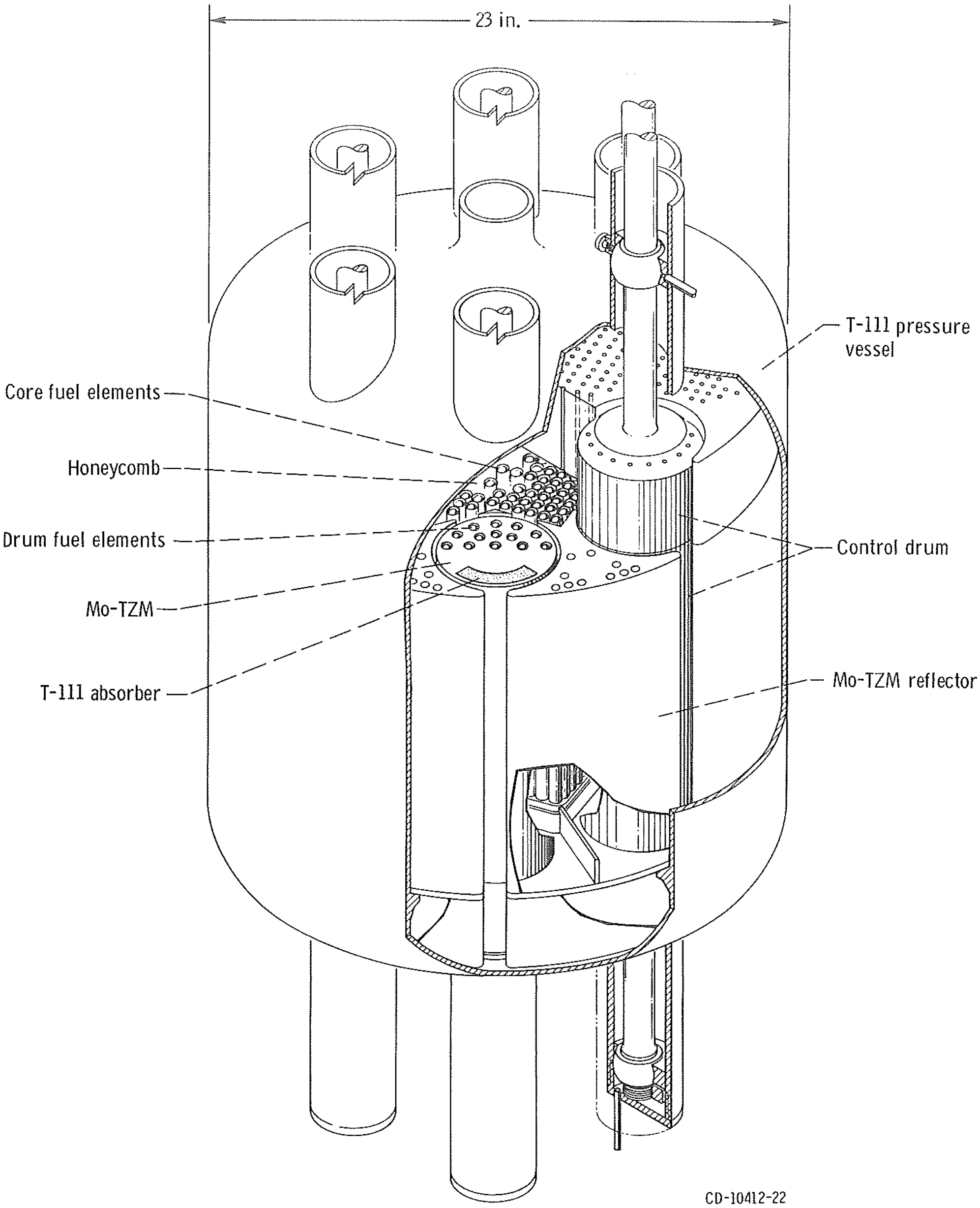

Figure 2. - Nuclear Brayton space power reactor.

TABLE I. - DESIGN POINT OPERATING CONDITIONS

Reactor thermal power, mW	2.17
Lithium temperature at reactor inlet, ^{o}R (K)	2100 (1167)
Lithium temperature at reactor outlet, ^{o}R (K)	2200 (1222)
Lithium flow rate, lbm/sec (kg/sec)	20.7 (9.39)

AUXILIARY LOOP

General Considerations

Following a shutdown of the nuclear reactor, decay heat continues to be generated in the reactor core at a rate which depends primarily on (1) the reactor's initial operating power level, and (2) the period of time during which the reactor was in operation before the shutdown. In a space power reactor, the decay heat must ultimately be rejected to space by some type of waste-heat radiator.

It may be both impractical and undesirable to use the main radiator loop of the system (fig. 1) as a primary scheme for rejection of decay heat. It is conceivable that a shutdown may be caused by a failure in the main radiator loop. In such case, it may be impossible to use the main radiator. Furthermore, it may be desirable in the system design to have a method for rejection of decay heat which is independent of the main system operation.

Auxiliary Loop Description

One scheme for rejecting the decay heat is to use a liquid-metal auxiliary radiator loop. Figure 3 shows a sodium-cooled auxiliary loop which is connected to the reactor primary loop by an auxiliary heat exchanger. The auxiliary loop consists of a high-temperature auxiliary radiator, an auxiliary heat exchanger, a liquid-sodium pump, and the necessary flow control valves and piping. Sodium was selected as the coolant in the auxiliary loop because it has a reasonably low melting point and also a relatively low vapor pressure for the temperatures which we will be considering.

During normal system operation, nearly all the heat generated in the reactor is transferred to the gas power conversion loop. But when a shutdown occurs, the decay heat generated in the reactor must be transferred to the auxiliary loop. To accomplish this, the flow of lithium in the primary loop must be bypassed around the heat-source heat exchanger; and the sodium flow rate in the auxiliary loop must be increased to transfer the decay heat. Hence, the auxiliary loop undergoes a transient startup immediately following the reactor shutdown.

Operating Assumptions

To investigate the operation of this loop, some assumptions were made regarding the initial conditions in the loop and the mode of operation of this loop during the reactor

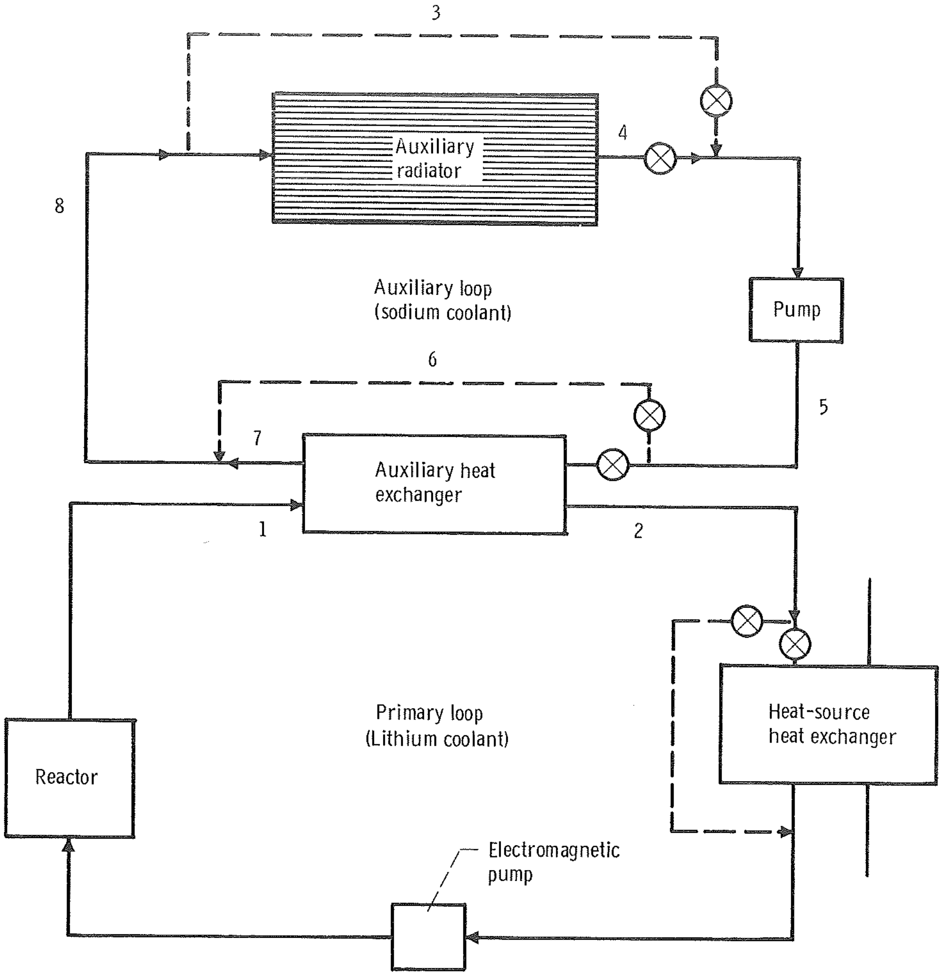

Figure 3. - Primary loop with auxiliary radiator loop for decay heat rejection. (See appendix for number designations.)

shutdown transient. For the preliminary investigation presented herein, we assume that the shutdown is not the result of a serious failure and that, as a consequence, the system is capable of being restarted and returned to its design operating condition.

As a point of interest, the restarting of this fast-spectrum reactor is, in some respects, less complicated than that of a thermal-spectrum reactor. This is because the xenon-135 and samarium-149 concentrations, which build up after shutdowns, do not act as strong absorbers (i.e., their absorption cross sections are small) for high-energy neutrons. And the problem of overriding the poisoning effects of these isotopes is far less serious in this reactor.

The major assumptions used in this preliminary analysis and related to the operating conditions are listed below:

(1) The lithium temperature at the reactor inlet is maintained constant at 2100° R (1167 K) during the shutdown. (This is the design point operating temperature (table I).)

(2) The lithium temperature at the reactor outlet is held constant at 2200° R (1222 K) during shutdown. (This is also the design point operating temperature (table I).)

(3) The initial temperature of sodium in the auxiliary loop at shutdown is 100° R (55.6 K) above the melting temperature of sodium, or 770° R (428 K).

(4) In order to keep the auxiliary loop temperatures reasonably uniform after shutdown, we assume the mixed-mean temperature difference across the auxiliary heat exchanger to be constant at 100° R (55.6 K); that is, $(T_{Na,8} - T_{Na,5}) = 100^{\circ}$ R (55.6 K). (All symbols are defined in appendix A.)

(5) A maximum allowable sodium temperature of 1760° R (978 K) at the auxiliary radiator inlet is assumed.

Assumptions (1) and (2) are consistent with a requirement that the system be capable of being restarted in a minimum time. Maintaining the primary loop temperatures at their respective design values will minimize the time required to return the system to its design operating level.

The selection of an auxiliary loop temperature of 770° R (428 K) (assumption (3)) was based on several considerations. First, this initial (or standby) temperature level of 770° R (428 K) gives a reasonable margin of safety against freezing of sodium in the auxiliary loop. At the same time, this temperature is low enough during standby operation that the heat rejected by the auxiliary radiator (which is a parasitic thermal load) is small relative to the reactor design thermal power.

Assumptions (4) and (5) limit the operating temperature and the differential temperature in the auxiliary loop. These values should not be considered as absolute limits. They were selected somewhat arbitrarily for this preliminary investigation in order to place some constraint on the operating conditions in the auxiliary loop during the decay heat removal period.

Auxiliary Loop Flow Models

In order to make a preliminary investigation of this loop, simplified flow models were developed to represent the auxiliary radiator and auxiliary heat exchanger. The auxiliary loop material (including the auxiliary heat exchanger, auxiliary radiator, and piping) is assumed to be tantalum. All tantalum physical properties used were taken from reference 2. A description of the flow models is given below.

Auxiliary heat exchanger. - The auxiliary heat exchanger is a counterflow type, consisting of two concentric cylindrical ducts. Figure 4 is a sketch of the auxiliary heat exchanger. Lithium is assumed to flow through the inner passage, and sodium flows

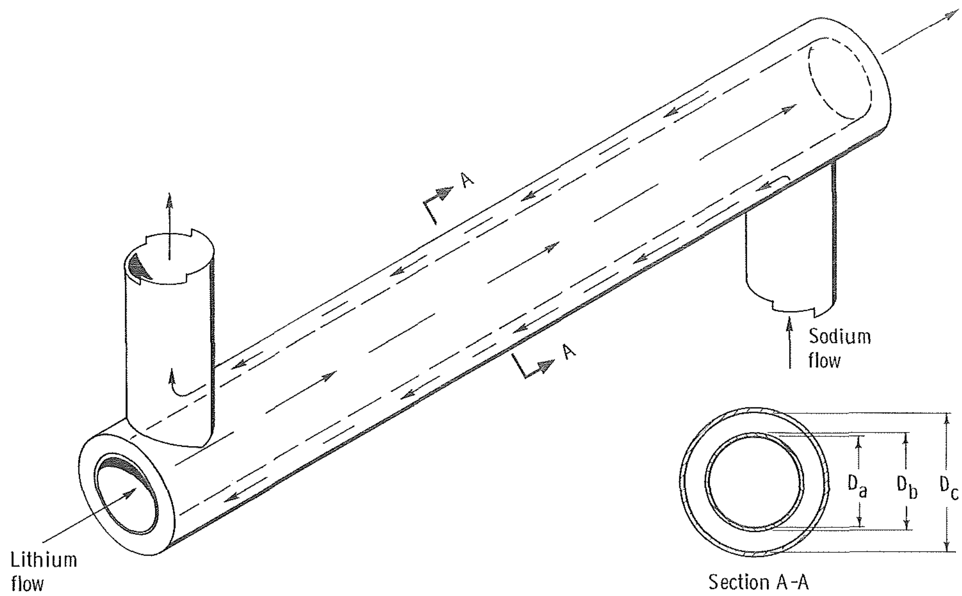

Figure 4. - Auxiliary heat exchanger flow model.

TABLE II. - AUXILIARY HEAT EXCHANGER CROSS-

SECTIONAL CONFIGURATION

Inside diameter of lithium passage, in. (cm)	1.25 (3.17)
Inside diameter of sodium annular flow passage, in. (cm)	1.35 (3.43)
Outside diameter of sodium annular flow passage, in. (cm)	1.84 (4.68)

countercurrently in the annular passage. Based on preliminary estimates of the area requirements of this heat exchanger, a cross-sectional configuration was selected. The cross-sectional configuration is described in table II.

Auxiliary radiator. - The auxiliary radiator is made up of a number of coplanar parallel tubes with central connecting fins. For this study, the effectiveness of the fins was assumed to be 100 percent. A sketch of the auxiliary radiator configuration is shown in figure 5.

Preliminary estimates were made to determine the area requirements and a reasonable planform configuration for the auxiliary radiator. From these estimates, a cross-sectional configuration was selected. It is based on the assumption that heat is rejected

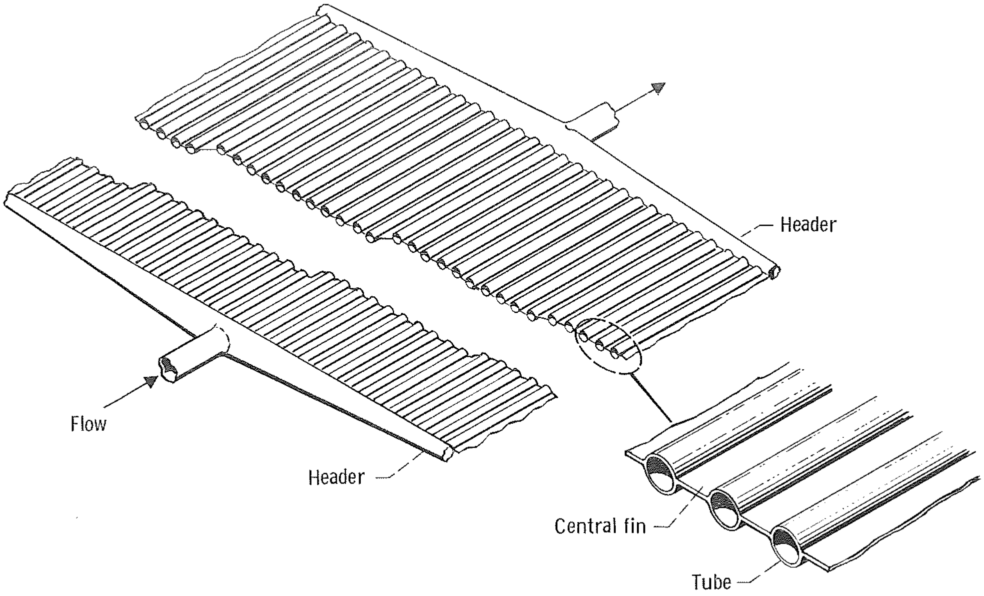

Figure 5. - Auxiliary radiator flow model.

TABLE III. - AUXILIARY RADIATOR CROSS-SECTIONAL CONFIGURATION

Number of tubes	24
Outside diameter of tubes, in. (cm)	1 (2.54)
Inside diameter of tubes, in. (cm)	0.875 (2.22)
Spacing between tubes (or central fin width), in. (cm)	1.055 (2.68)
Central fin thickness, in. (cm)	1/16 (0.159)

to space from both sides of the auxiliary radiator. A description of the auxiliary radiator cross-sectional configuration is given in table III.

The central fin width (1.055 in. or 2.68 cm) was chosen for convenience. With this fin width, the surface area of all tubes is equivalent to the product of total radiator surface area (which includes tubes and connecting fins) and the configuration factor from the auxiliary radiator to space.

ANALYSIS

Heat-Transfer Correlations

The correlations used to compute the rate of heat flow in the auxiliary loop are de-

scribed below. The heat-transfer coefficient on the lithium side of the auxiliary heat exchanger was computed from the correlation (ref. 3)

$$Nu_{Li} = 5 + 0.025\left(Re_{Li}\right)^{0.8}\left(Pr_{Li}\right)^{0.8} \tag{1}$$

The lithium properties used in this study were obtained from reference 4.

The sodium heat-transfer coefficient of the annular flow passage was determined from the equation (ref. 5).

$$Nu_{Na} = 0.8\left(\frac{D_c}{D_b}\right)^{0.3}\left[5.1 + 0.028\left(Pe_{Na}\right)^{0.8}\right] \tag{2}$$

The physical properties of sodium were taken from reference 6.

The overall heat-transfer coefficient for the auxiliary heat exchanger, based on the surface area of the sodium side, is given by

$$U_b = \frac{1}{\frac{D_b}{D_a}\left(\frac{1}{h_{Li}}\right) + \frac{D_b \ln\left(\frac{D_b}{D_a}\right)}{2k_m} + \frac{1}{h_{Na}}} \tag{3}$$

In the auxiliary radiator, an infinite heat-transfer coefficient was assumed on the liquid-sodium side of the flow passages. This assumption is discussed later in this section.

Analytical Equations

Primary loop. - The lithium flow rate required to maintain a constant temperature difference of 100° R (55.6 K) across the core at any time t after shutdown is given by

$$\dot{w}_{Li} = \frac{Q}{C_{p,Li}\left(T_{Li,1} - T_{Li,2}\right)} \tag{4}$$

where $T_{Li,1} = 2200^{\circ}$ R (1222 K) and $T_{Li,2} = 2100^{\circ}$ R (1167 K). In equation (4), Q is the decay heat generation rate, which varies with time after shutdown.

Auxiliary loop. - The total flow rate of sodium needed to maintain a constant mixed-

mean temperature difference of 100° R (55.6 K) in the auxiliary loop at any time t after shutdown is given by

$$\dot{w}_{Na,5} = \dot{w}_{Na,8} = \frac{Q}{C_{p,Na}(T_{Na,8} - T_{Na,5})} \tag{5}$$

From operating assumption number (4) in the section AUXILIARY LOOP, $(T_{Na,8} - T_{Na,5})$ is constant and equal to 100° R (55.6 K) throughout the shutdown period.

The decay heat generation rate and the overall lithium-to-sodium temperature difference across the auxiliary heat exchanger change with time following a shutdown. Consequently, the flow rate of sodium in the auxiliary heat exchanger $\dot{w}_{Na,7}$ must also change with time. The sodium flow rate needed to transfer the decay heat from primary loop to auxiliary loop at any time t after shutdown was determined from the equation

$$\dot{w}_{Na,7} = \frac{Q}{EC_{p,Na}(T_{Li,1} - T_{Na,5})} \tag{6}$$

The sodium flow rate which bypasses the auxiliary heat exchanger is the difference between the total sodium flow rate and the sodium flow rate which goes through the auxiliary heat exchanger; that is,

$$\dot{w}_{Na,6} = \dot{w}_{Na,5} - \dot{w}_{Na,7} \tag{7}$$

The effectiveness of the counterflow auxiliary heat exchanger (E in eq. (6)) is also time variant, and is defined by the following expression (ref. 7):

$$E = \frac{1 - \exp\left[\frac{U_b A_b}{C_{p,Na}\dot{w}_{Na,7}}\left(1 - \frac{C_{pNa}\dot{w}_{Na,7}}{C_{pLi}\dot{w}_{Li}}\right)\right]}{1 - \left(\frac{C_{pNa}\dot{w}_{Na,7}}{C_{pLi}\dot{w}_{Li}}\right)\exp\left[-\frac{U_b A_b}{C_{pNa}\dot{w}_{Na,7}}\left(1 - \frac{C_{pNa}\dot{w}_{Na,7}}{C_{pLi}\dot{w}_{Li}}\right)\right]} \tag{8}$$

The sodium temperature at the outlet of the auxiliary heat exchanger was determined from the equation

$$T_{Na,7} = T_{Na,6} + \frac{Q}{\dot{w}_{Na,7}C_{pNa}} \tag{9}$$

For calculational purposes, the flow passages in the auxiliary radiator were considered to be made up of a number of equal length segments arranged in series. (The actual cross-sectional configuration of this radiator is described in table III.) A sketch

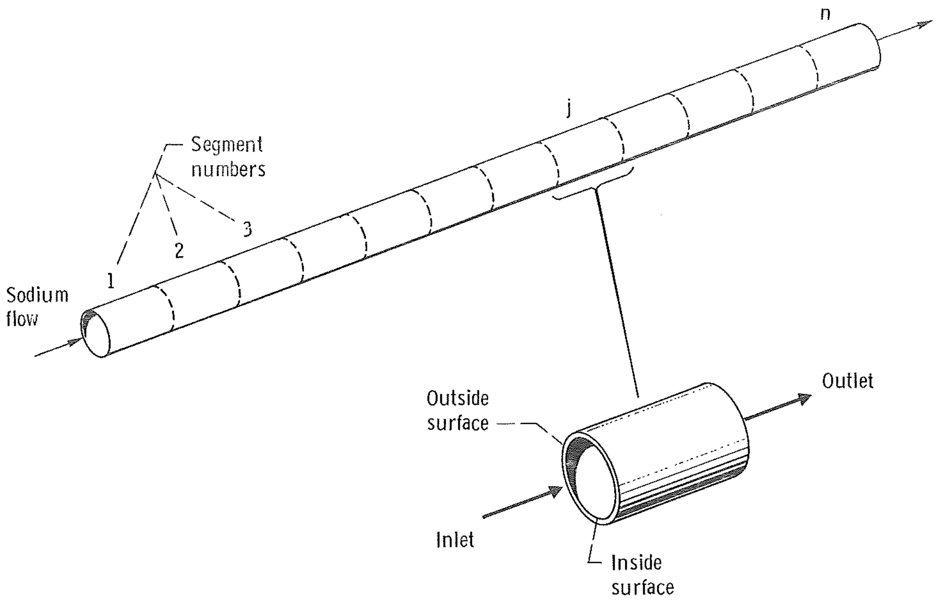

Figure 6. - Analytical model used to represent auxiliary radiator.

of the analytical model for the auxiliary radiator is shown in figure 6. As indicated in the figure, each tube in the auxiliary radiator was assumed to be made up of "n" segments. A segment length of 1.8 inches (4.57 cm) was used in the analysis. The reason for using a segment length of 1.8 inches or 4.57 cm is given later in this section.

The following assumptions were used in the auxiliary radiator calculations:

(1) The temperature drop through the auxiliary radiator tube wall is negligible.

(2) Heat conduction along the length of the auxiliary radiator is negligible.

(3) Only the thermal capacitance of the auxiliary radiator (which includes tubes and fins) is considered.

(4) Sink temperature is constant and equal to 400° R (222 K).

(5) Radiator surface emissivity ϵ is equal to 0.80.

With steady flow in the auxiliary radiator, an energy balance on a typical segment (e.g., segment j) is

$$\left(\begin{array}{l}\text{Rate of change of}\\ \text{sodium internal}\\ \text{energy across}\\ \text{segment } j\end{array}\right) = \left(\begin{array}{l}\text{Rate of heat trans-}\\ \text{fer from sodium}\\ \text{to radiator wall}\\ \text{in segment } j\end{array}\right) = \left(\begin{array}{l}\text{Rate of change in}\\ \text{sensible heat of}\\ \text{radiator seg-}\\ \text{ment } j\end{array}\right) + \left(\begin{array}{l}\text{Rate of heat re-}\\ \text{jection by radi-}\\ \text{ator segment } j\\ \text{to sink}\end{array}\right)$$

Or, in equation form,

$$-\dot{w}_{Na,4}C_{pNa}\,dT_{Na,j} = h_R\,\Delta A_i(\overline{T}_{Na,j} - \overline{T}_{R,j})$$

$$= \Delta M_j C_M \frac{d\overline{T}_{R,j}}{d\tau} + \sigma\epsilon\,\Delta A_o\left(\overline{T}^4_{Na,j} - T^4_s\right) \tag{11}$$

In equation (11) the subscripts i and o on ΔA refer to the inside and outside surfaces of the radiator tubes (see fig. 6).

With liquid-sodium flow, the wall-to-bulk temperature difference in the auxiliary radiator tubes is relatively small. (For a radiator temperature of 1700° R (944 K), the wall-to-bulk ΔT with turbulent flow is less than 10° R (5.56 K).) Therefore, we can neglect the liquid-metal film resistance and assume that $T_{R,j} = T_{Na,j}$ without introducing a significant error. And equation (11), in finite-difference form, becomes

$$\dot{w}_{Na,4}C_{pNa}(T_{Na,j,in} - T_{Na,j,out}) = \Delta M_j C_M \frac{\Delta\overline{T}_{Na,j}}{\Delta\tau} + \sigma\epsilon\,\Delta A_o\left(\overline{T}^4_{Na,j} - T^4_s\right) \tag{12}$$

where

$$\overline{T}_{Na,j} = \frac{T_{Na,j,in} + T_{Na,j,out}}{2} \tag{13}$$

The sodium flow rate in the bypass around the auxiliary radiator is given by

$$\dot{w}_{Na,3} = \dot{w}_{Na,5} - \dot{w}_{Na,4} \tag{14}$$

The mass of each radiator segment (i.e., the value of ΔM in eq. (11)) was determined from the cross-sectional configuration listed in table III along with the assumed length of the segments. As stated earlier in this section, only the mass of the auxiliary radiator (which includes tubes and fins) was considered in the study; and the thermal capacitance of the auxiliary heat exchanger, inlet plenums, valves, and piping were ignored.

The time interval $\Delta\tau$ used in equation (12) is equal to the auxiliary loop transport delay (or delay time). The transport delay is defined as the time required for the sodium coolant to traverse the auxiliary loop. Expressed as an equation,

$$\Delta\tau = \frac{\text{Total volume of auxiliary loop}}{\text{Sodium volumetric flow rate}} \tag{15}$$

or

$$\Delta\tau = \frac{(\text{Volume of auxiliary radiator}) + (\text{Volume of auxiliary loop flow lines})}{\dfrac{\dot{w}_{Na,5}}{\rho_{Na}}} \tag{16}$$

A volume of 0.260 cubic feet (0.02835 m^3) was assumed for the auxiliary loop flow lines. This volume is equivalent to that of a 1.5-inch- (3.81-cm-) inside-diameter pipe with a length of about 21 feet (5.1 m).

The volume of the auxiliary radiator is equal to the product of the auxiliary radiator flow area and length. The flow area is obtained from table III, and the procedure used to determine the length of the auxiliary radiator is described later in this section.

Analytical Procedure

A digital computer code was written to analyze the decay heat removal from the primary loop of the nuclear space powerplant. For purposes of analysis, the removal of decay heat from the primary loop can be considered to take place in two sequential steps. First, for some period of time immediately following a shutdown, most of the decay power goes to increasing the sensible heat of the sodium-cooled auxiliary loop. During this period, the sodium flow rates through and around the auxiliary heat exchanger (fig. 3) are regulated such that the mixed-mean sodium temperature rise across the auxiliary heat exchanger is 100° R (55.6 K). (This is consistent with operating assumption (4) in the section AUXILIARY LOOP.) Throughout this auxiliary loop heat-up period, the total flow of sodium passes through the auxiliary radiator. And the auxiliary loop temperature is raised from its initial value of 770° R (428 K) to some selected final operating temperature. (In the section AUXILIARY LOOP, a maximum allowable sodium temperature of 1760° R (978 K) at the auxiliary radiator inlet was assumed.)

The second part of the decay heat removal period begins when the sodium temperature at the auxiliary radiator inlet reaches its final operating temperature. Then, the mixed-mean sodium temperatures in the auxiliary loop ($T_{Na,5}$ and $T_{Na,8}$ in fig. 3) are held at their respective levels by regulating the flow rates of sodium through and around the auxiliary heat exchanger and auxiliary radiator. A sketch of the typical history of the sodium temperature at the auxiliary heat exchanger inlet following a shutdown is shown in figure 7.

In the following paragraphs, we describe the procedure used in the decay heat removal analysis. Decay heat generation rates for the space power reactor were calculated for several full-power operating time periods. The method of calculating the decay heat

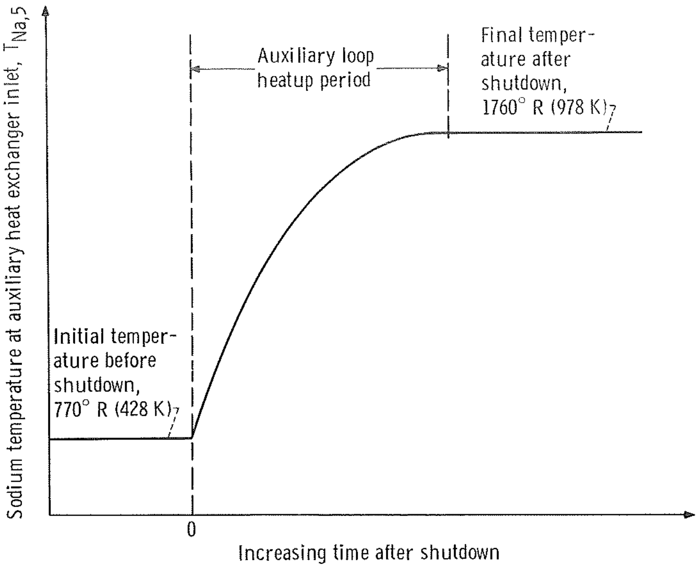

Figure 7. - Typical history of sodium temperature at auxiliary heat exchanger inlet as function of time after shutdown.

rates is described in reference 8. From these calculated values, an upper and lower limit for decay heat generation rate was determined. The upper limit corresponds to a reactor full-power operating period of 1 year; the lower limit corresponds to a full-power operating period of 1 day.

An iterative technique was used to determine the minimum areas required by the auxiliary heat exchanger and auxiliary radiator. The upper limit of decay heat generation was used as the basis for these calculations. The calculations were made by picking trial values of area (or length) for the auxiliary loop heat exchanger and radiator.

With these trial values, flow rates and temperatures were calculated in the auxiliary loop as a function of time after shutdown.

The temperatures and flow rates obtained were then used as guidelines to update the areas (or lengths) of the auxiliary heat exchanger and auxiliary radiator. The calculations were then repeated with the updated areas. This calculational procedure (in which successive computations were made with updated values of area or length) was continued until the final areas (or lengths) obtained were minimum values consistent with the established temperature limitations for the auxiliary loop.

The flow rate in the auxiliary heat exchanger $w_{Na,7}$ was calculated as a function of time after shutdown from equations (6) and (8). An iterative technique was used to solve these equations for each trial value of auxiliary heat exchanger area.

The sodium temperature at the auxiliary radiator outlet $T_{Na,4}$ was determined by numerically integrating equation (11) from auxiliary radiator inlet (segment 1) to outlet (segment n). As stated earlier in this section, the total sodium flow rate passes through

the auxiliary radiator during the auxiliary loop heatup period. But when the sodium temperature at the auxiliary radiator inlet reaches 1760° R (978 K), the decay heat generation rate must be balanced by the net rate of heat lost by the sodium in the auxiliary radiator. This criterion was used to determine the minimum area (or length) of the auxiliary radiator.

After the sodium temperature at the auxiliary radiator inlet reaches 1760° R (978 K), a part of the total sodium flow must be bypassed around the auxiliary radiator in order to maintain the proper heat rejection rates. The flow rates through and around the auxiliary radiator were calculated from equations (12) and (14). An iterative procedure was used to determine these flow rates as a function of time.

The numerical open-loop integration of equation (12) is subject to a cumulative error. The significance of the error depends primarily on (1) the size and/or number of segments used to represent the auxiliary radiator, and (2) the number of numerical integrations carried out.

The magnitude of this cumulative error was investigated by using radiator segments with lengths ranging from 0.72 to 7.2 inches (1.83 to 18.3 cm). From this investigation, it was determined that a segment length of 1.8 inches (4.57 cm) gives a reasonably accurate representation of the auxiliary loop variables, provided the shutdown times used in the analysis are relatively short (i.e., on the order of 3 hr (10 800 sec) or less).

All calculations required in this quasi-steady-state analysis were performed on a high-speed digital computer. In table IV, we have summarized the values used for the input variables in this analysis. These input values have been stated and discussed in previous sections of this report.

TABLE IV. - SUMMARY OF VALUES USED IN ANALYSIS

Radiator surface emissivity, ϵ	0.80
Sink temperature, T_s, $^{\circ}$R (K)	400 (222)
Lithium temperature at reactor inlet, $T_{Li,1}$, $^{\circ}$R (K)	2100 (1167)
Lithium temperature at reactor outlet, $T_{Li,2}$, $^{\circ}$R (K)	2200 (1222)
Initial temperature of auxiliary loop prior to shutdown, $^{\circ}$R (K)	770 (428)
Sodium mixed-mean temperature difference, $T_{Na,8} - T_{Na,5}$, $^{\circ}$R (K)	100 (55.6)
Maximum allowable sodium temperature at auxiliary radiator inlet, $T_{Na,8}$, $^{\circ}$R (K)	1760 (978)

RESULTS AND DISCUSSION

Decay heat generation rates in the nuclear space power reactor were calculated as a function of time following reactor shutdown. Figure 8 shows the ratio of reactor decay power to steady-state design power against time after reactor shutdown. The parameter in figure 8 is the reactor full-power operating time before shutdown.

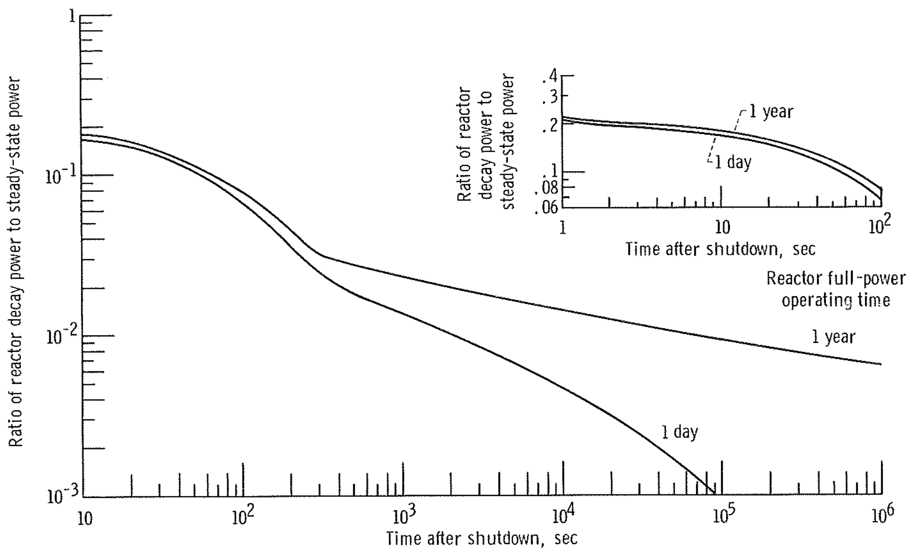

Figure 8. - Ratio of reactor decay power to steady-state power against time after shutdown with reactor full power operating time as a parameter.

The lithium flow rates required to maintain a constant lithium temperature difference of 100° R (55.6 K) across the reactor core are shown against time after shutdown in figure 9. These flow rates were calculated from equation (4), and are based on the reactor design operating power of 2.17 megawatts-thermal.

As explained in the section ANALYSIS, the upper limit of decay heat generation (which corresponds to 1 year of reactor full-power operation before shutdown) was used to determine the area requirements of the auxiliary heat exchanger and auxiliary radiator. From the procedure described in the section ANALYSIS, the following area and/or length requirements were determined:

For the auxiliary heat exchanger,
Length, L_{HX}, ft (m) 1.81 (0.552)
Heat-transfer surface area, $A_{s,b}$, ft^2 (m^2). 0.64 (0.0594)

(The cross-sectional configuration of the auxiliary heat exchanger is described in table II.)

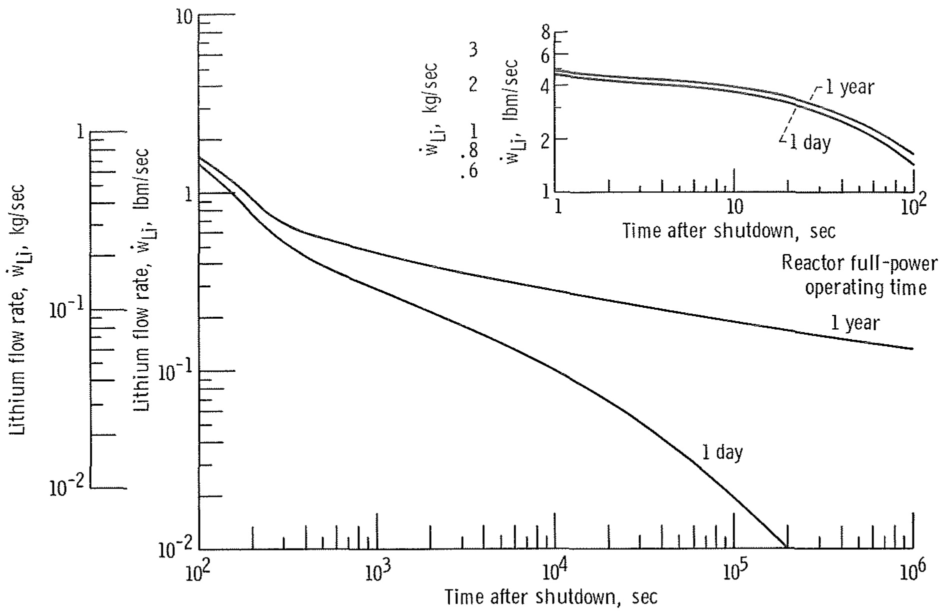

Figure 9. - Lithium flow rate against time after shutdown with reactor full power operating time as a parameter. Lithium temperature rise across core constant at 100° R (55.5 K).

For the auxiliary radiator,

Planform length, L_{Rad}, ft (m)	6.0 (1.83)
Effective radiation area (both sides), ft^2 (m^2)	37.7 (3.50)
Planform width (tubes and fins), ft (m)	3.14 (0.958)

(The cross-sectional configuration of the auxiliary radiator is described in table III.) From the cross-sectional configuration and the value of L_{Rad}, the total mass of the auxiliary radiator (which includes tubes and fins only) was calculated to be approximately 225 pounds (102 kg).

The auxiliary radiator mass and the heat-transfer surface areas just listed were used to determine flow rates and temperatures in the auxiliary loop as a function of time after shutdown. Two sets of data were calculated. One set was based on a reactor full-power operating time of 1 year; the other set was for a full-power operating time of 1 day. In the following paragraphs, we present data for each of these reactor operating times.

Reactor Operating Time of 1 Year

Calculated sodium flow rates and temperatures in the auxiliary loop are shown as a function of time after reactor shutdown in figures 10 to 14. These data (figs. 10 to 14)

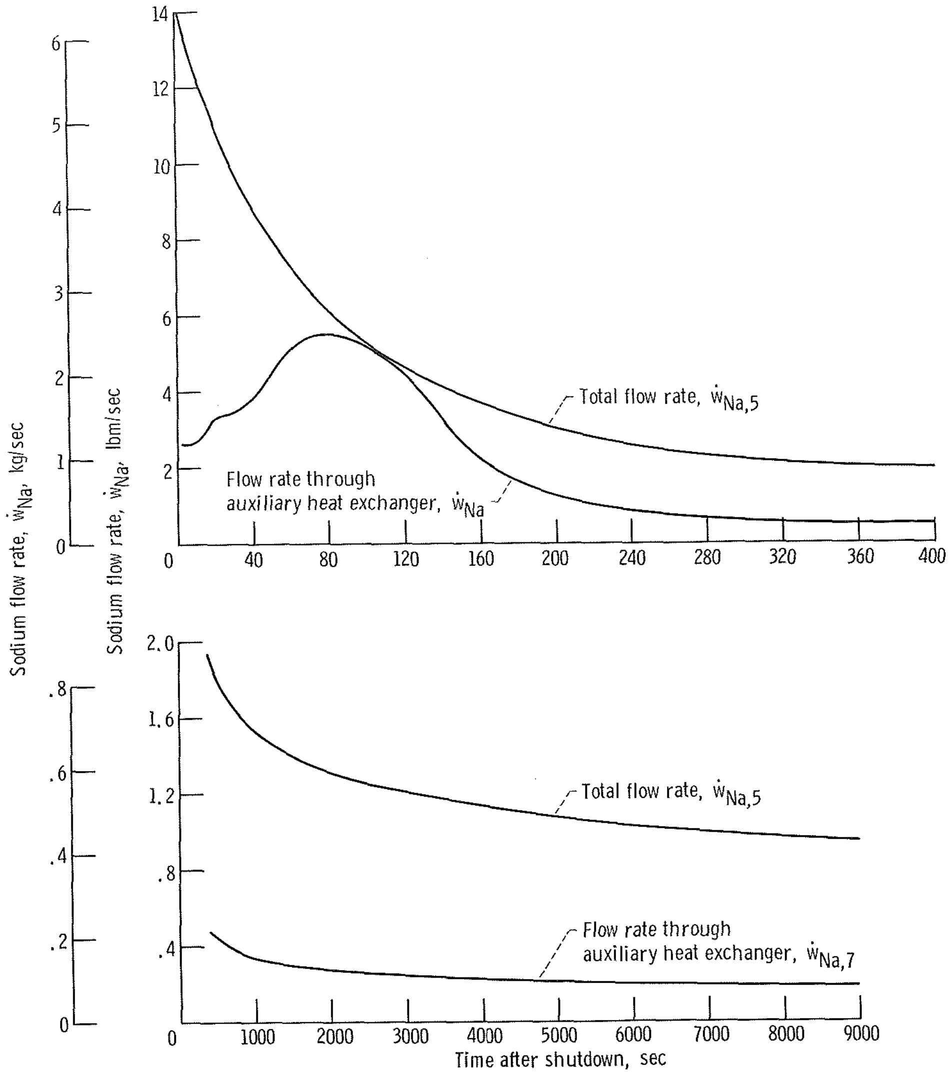

Figure 10. - Total sodium flow rate in auxiliary loop and sodium flow rate in auxiliary heat exchanger against time after shutdown. Reactor operating time, 1 year; reactor power, 2.17 megawatts-thermal.

are based on a reactor operating time of 1 year before shutdown.

The total flow rate of sodium in the auxiliary loop and the flow rate which passes through the auxiliary heat exchanger are shown against time in figure 10. The difference between the two flow rates is equal to the auxiliary heat exchanger bypass flow rate; that is, $\dot{w}_{Na,6} = \dot{w}_{Na,8} - w_{Na,7}$ at any time t after shutdown.

At approximately 106 seconds after shutdown, the difference between the curves in figure 10 approaches zero. And the bypass flow rate at this time is essentially zero. The fact that the curves in figure 10 are tangent at some time after shutdown signifies that the area (or length) assigned to the auxiliary heat exchanger is indeed a minimum for the configuration assumed and described in table II.

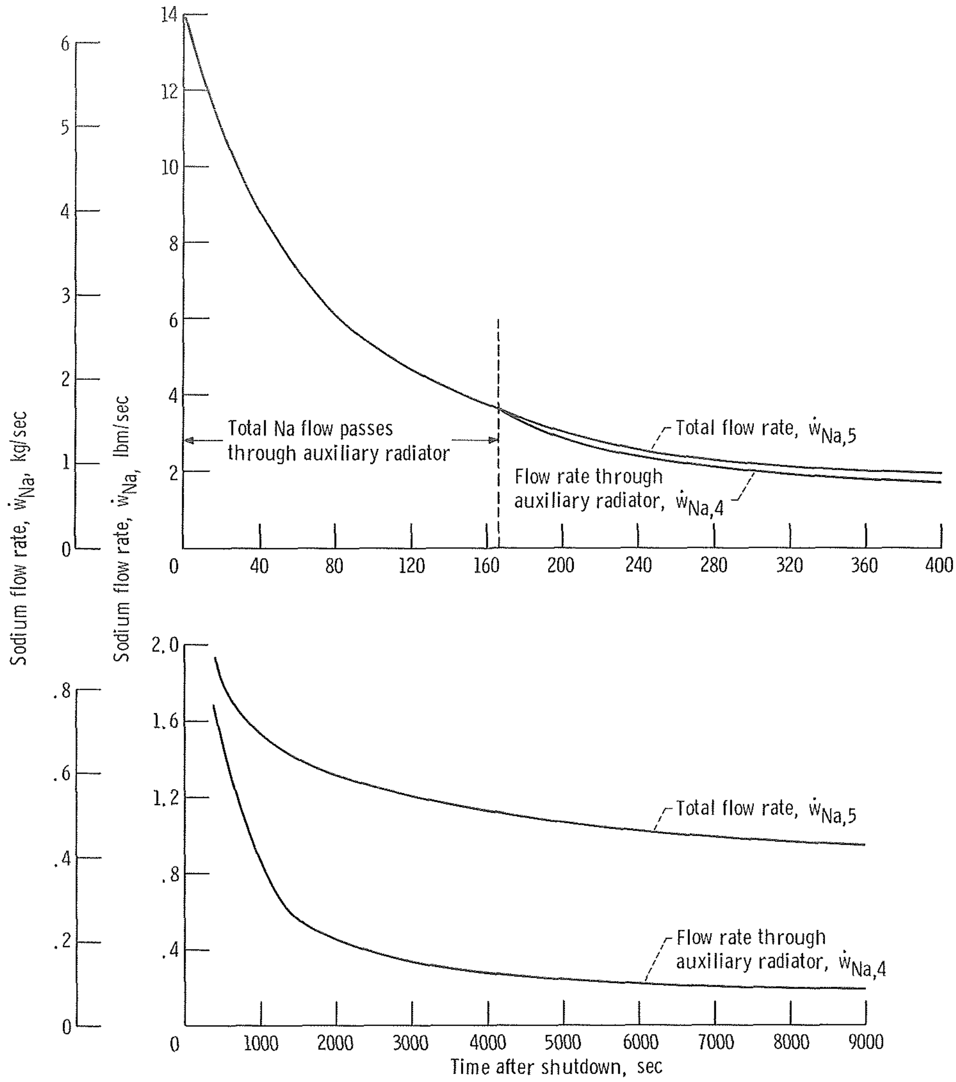

Figure 11. - Total sodium flow rate in auxiliary loop and sodium flow rate in auxiliary radiator against time after shutdown. Reactor operating time, 1 year; reactor power, 2.17 megawatts-thermal.

The total sodium flow rate in the auxiliary loop and the flow rate in the auxiliary radiator are shown as a function of time after shutdown in figure 11. As indicated in figure 11, for the time span from 0 to 166 seconds after shutdown, the total sodium flow passes through the auxiliary radiator. But for times greater than 166 seconds, a fraction of the total flow bypasses the auxiliary radiator. The bypass flow rate $\dot{w}_{Na,3}$ is the difference between the total flow rate $\dot{w}_{Na,8}$ and the flow rate through the auxiliary radiator $\dot{w}_{Na,4}$. Figure 11(b) shows that after $2\frac{1}{2}$ hours (9000 sec), only about 20 percent of the total sodium flow goes through the auxiliary radiator.

The mixed-mean temperatures of sodium at the auxiliary radiator inlet and auxiliary

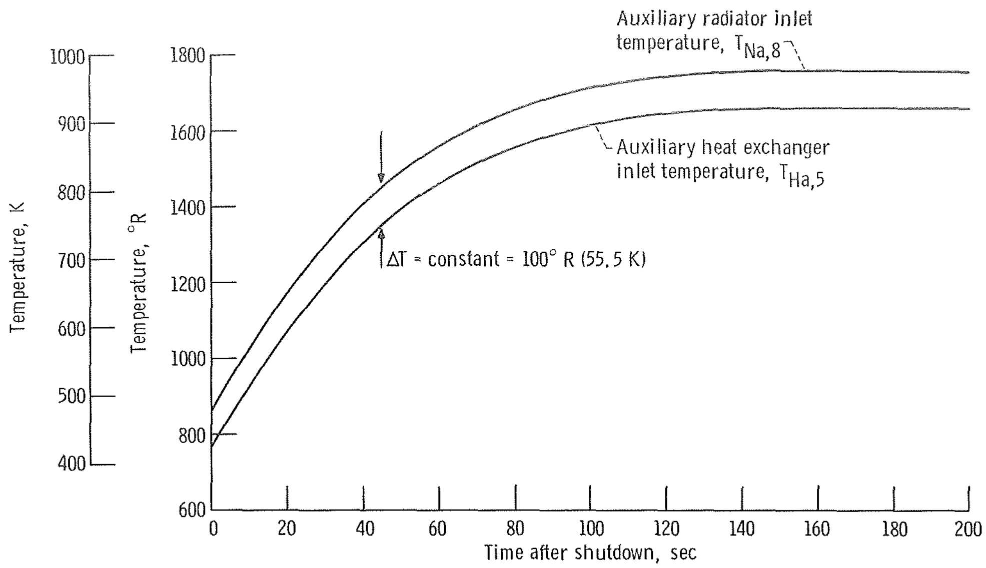

Figure 12. - Mixed-mean temperature of sodium at auxiliary radiator inlet and auxiliary heat exchanger inlet against time after shutdown. Reactor operating time, 1 year; reactor power, 2.17 megawatts-thermal.

heat exchanger inlet are shown against time after shutdown in figure 12. The difference in temperature between these curves at any time t (i.e., $T_{Na,8} - T_{Na,5}$) is constant and equal to 100° R (55.6 K) throughout the shutdown period. The slopes of the curves in figure 12 decrease with time and asymptotically approach a final value of zero. About 166 seconds are required before the mixed-mean temperatures ($T_{Na,8}$ and $T_{Na,5}$) reach their final values. For times greater than 166 seconds, the temperatures $T_{Na,8}$ and $T_{Na,5}$ are essentially constant and equal to 1760° R (978 K) and 1660° R (922 K), respectively.

The shapes of the curves in figure 12 are influenced primarily by the effectiveness of the auxiliary radiator and the decay heat input to the auxiliary loop. The auxiliary radiator effectiveness increases with temperature and/or time after shutdown, whereas the decay heat generation rate (fig. 8) decreases with time.

Figure 13 shows the sodium temperature at the auxiliary heat exchanger outlet against time after reactor shutdown. Shortly after a shutdown occurs, the sodium temperature at the auxiliary heat exchanger outlet is approximately 1300° R (722 K). It increases from this value at a significant rate during the first 400 seconds after shutdown; and thereafter it slowly approaches the maximum lithium temperature $T_{Li,1}$ in the primary loop.

During normal system operations (i.e., prior to a shutdown), a small flow rate of sodium is required in the auxiliary heat exchanger in order to keep the sodium mixed-mean temperatures at the assumed standby level of 760° R (372 K). Even with the low

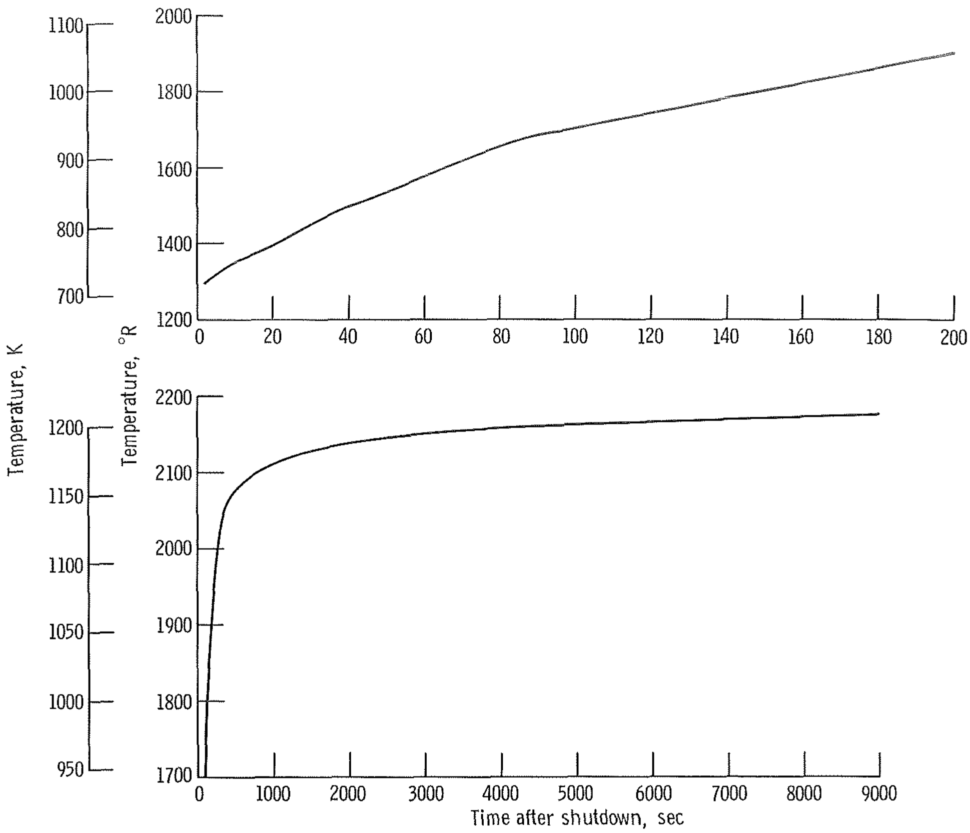

Figure 13. - Sodium temperature at auxiliary heat exchanger outlet against time after shutdown. Reactor operating time, 1 year; reactor power, 2.17 megawatts-thermal.

sodium flow rate which occurs during normal system operation, the liquid-sodium heat-transfer coefficient is relatively large. And as a result, the sodium temperature at the auxiliary heat exchanger outlet during normal system operation is near the maximum lithium temperature $T_{Li,1}$ of 2200° R (1222 K). Hence, immediately after a shutdown, a sudden change must occur in the auxiliary heat exchanger outlet temperature.

This momentary transient was not considered; and for this reason the temperature curve in figure 13 does not extend to the time zero point.

Figure 14 shows the sodium temperature at the auxiliary radiator outlet as a function of time after shutdown. The temperature $T_{Na,4}$ reaches a maximum of 1660° R (922 K) at about 166 seconds after shutdown. (As shown in figure 11, this time also corresponds to the initiation of bypass flow around the auxiliary radiator.) After about 166 seconds, the temperature $T_{Na,4}$ decreases with time. The reason for the gradual decrease in $T_{Na,4}$ is that the sodium flow rate which goes through the auxiliary radiator gets smaller with time. As a result, the dwell time of the sodium in the auxiliary radiator gets larger with time after shutdown.

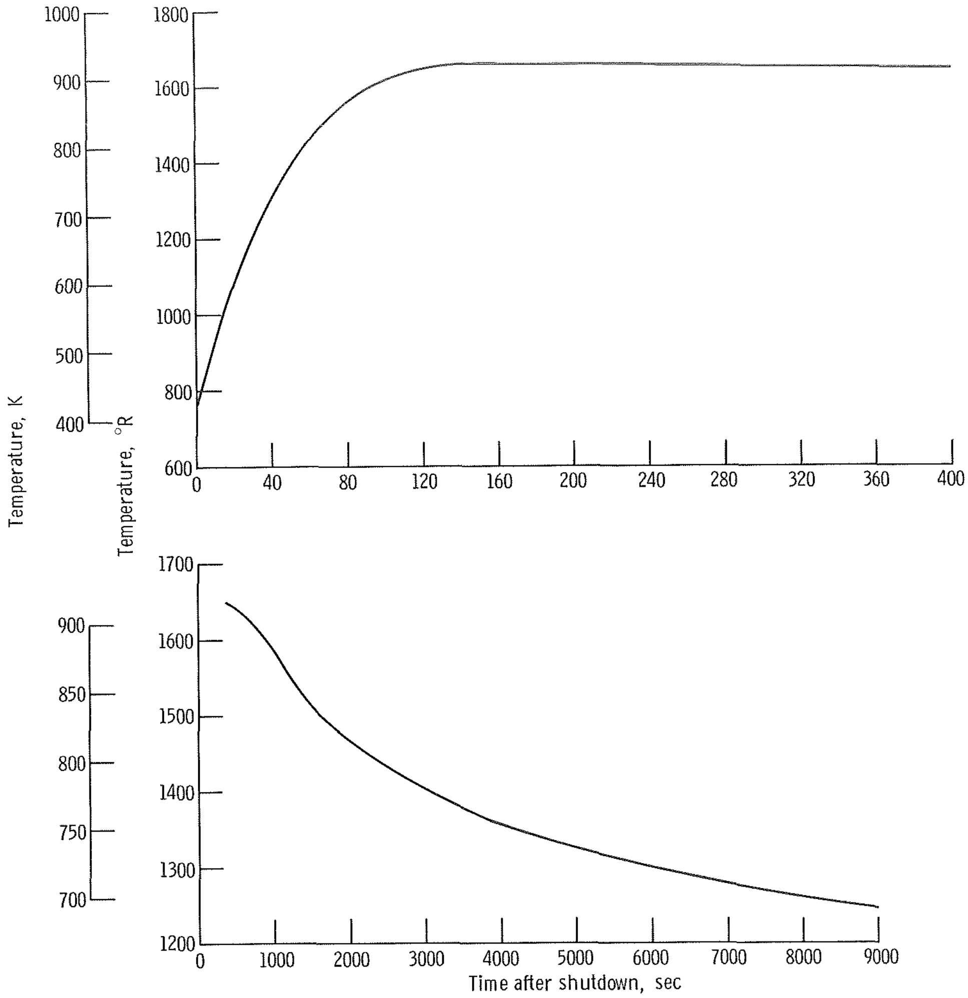

Figure 14. - Sodium temperature at auxiliary radiator outlet against time after shutdown. Reactor operating time, 1 year; reactor power, 2.17 megawatts-thermal.

Reactor Operating Time of 1 Day

The flow rates and temperatures of sodium in the auxiliary loop following a reactor full-power operating time of 1 day are shown in figures 15 to 19. Some of the data in these figures are similar to the data shown in figures 10 to 14 for a reactor operating time of 1 year.

The total flow rate of sodium in the auxiliary loop and the flow rate through the auxiliary heat exchanger are shown against time in figure 15. A comparison of figures 15 and 10 shows that the curves in figure 15 are not tangent at any point in time after shutdown; but in figure 10, the curves are tangent at approximately 106 seconds. The fact that the curves in figure 15 are not tangent signifies that the auxiliary heat exchanger area (A_{sb} = 0.64 ft^2 or 0.0594 m^2) is more than adequate to transfer the decay

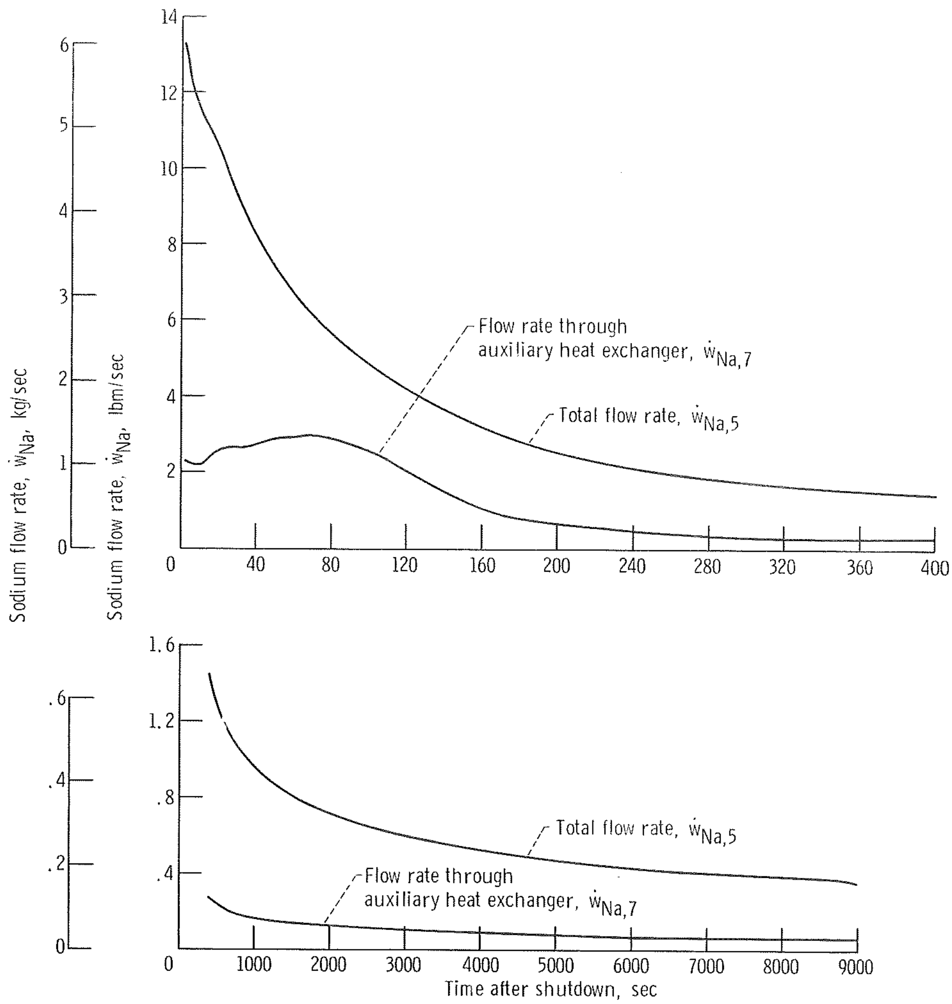

Figure 15. - Total sodium flow rate in auxiliary loop and sodium flow rate in auxiliary heat exchanger against time after shutdown. Reactor operating time, 1 day; reactor power, 2.17 megawatts-thermal.

heat to the auxiliary loop for a reactor preshutdown operating time of 1 day. Consequently, a large fraction of the total sodium flow rate bypasses the auxiliary heat exchanger throughout the shutdown. (The auxiliary heat exchanger bypass flow rate is the difference between the curves in fig. 15.)

Figure 16 shows the total sodium flow rate in the auxiliary loop and the sodium flow rate in the auxiliary radiator against time after shutdown. A comparison of figures 16 and 11 shows that the bypass flow around the auxiliary radiator begins at approximately the same time (about 166 sec after shutdown) for both reactor preshutdown operating times. This indicates that the ratios of heat rejection rate to decay heat input rate for the two preshutdown operating times are equal at about the same time after shutdown.

Figure 17 shows the mixed-mean sodium temperatures at the auxiliary radiator

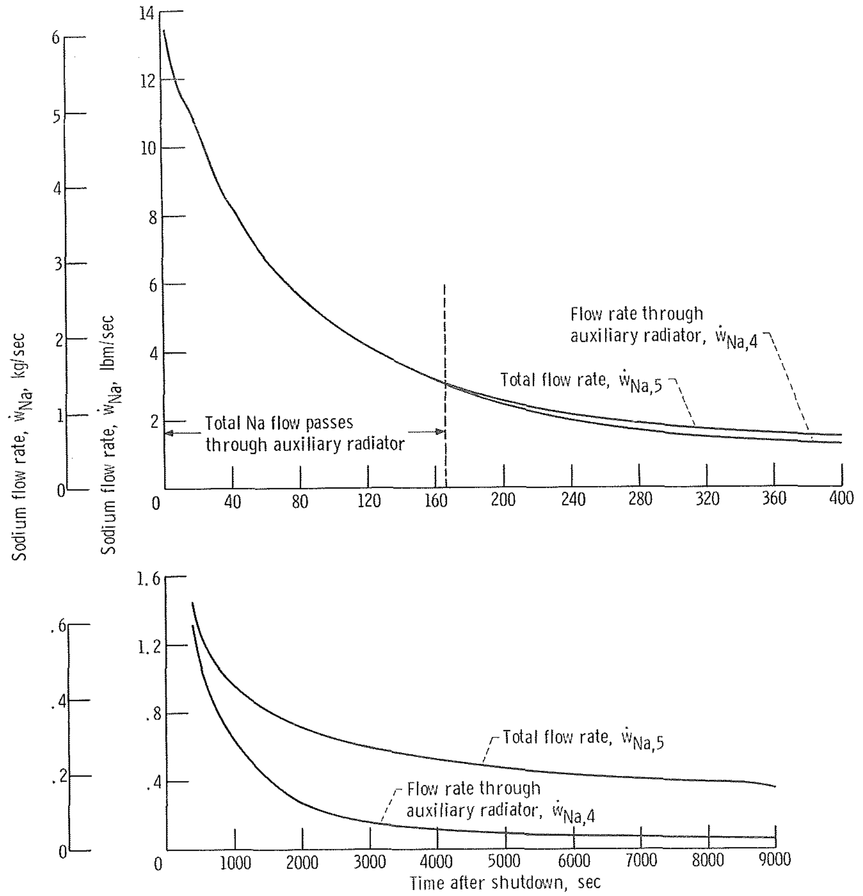

Figure 16. - Total sodium flow rate in auxiliary loop and sodium flow rate in auxiliary radiator against time after shutdown. Reactor operating time, 1 day; reactor power, 2.17 megawatts-thermal.

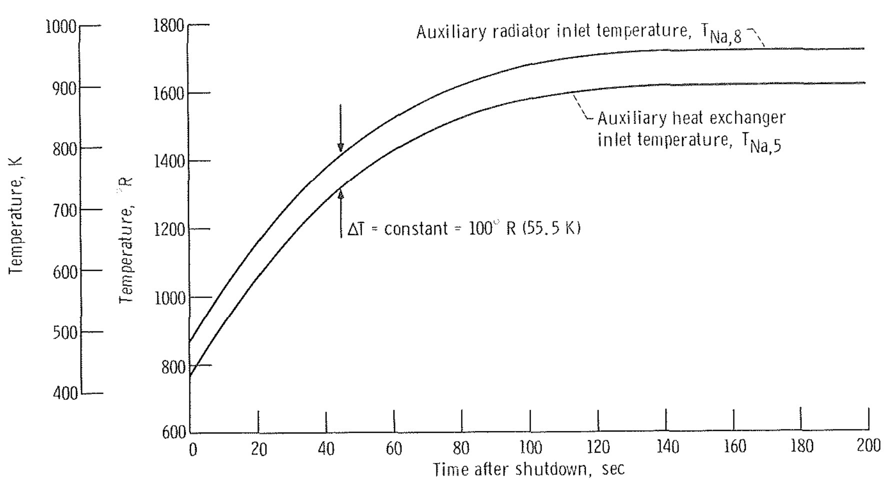

Figure 17. - Mixed-mean temperature of sodium at auxiliary radiator inlet and auxiliary heat exchanger inlet against time after shutdown. Reactor operating time, 1 day; reactor power, 2.17 megawatts-thermal.

inlet and auxiliary heat exchanger inlet against time after shutdown. The temperatures in figure 17 increase with time and reach their final values at approximately 166 seconds after shutdown. After 166 seconds, the temperatures $T_{Na,8}$ and $T_{Na,5}$ are essentially constant and equal to 1710° and 1610° R (950 and 894 K), respectively. These final temperatures are approximately 50° R (27.8 K) lower than those shown in figure 12.

The sodium temperature at the auxiliary heat exchanger outlet is shown against time after shutdown in figure 18. This temperature curve is similar to that shown in figure 13.

Figure 19 shows the sodium temperature at the auxiliary radiator outlet against time after shutdown. The temperature $T_{Na,4}$ reaches a maximum of 1610° R (894 K) at about 166 seconds after shutdown. (Figure 16 shows that this time also corresponds to the initiation of bypass flow around the auxiliary radiator.) After 166 seconds, the temperature $T_{Na,2}$ decreases gradually with time.

From a control standpoint, the range of sodium flow rates required during the shutdown period is important. The calculated data show that some of the sodium flow rates in the auxiliary loop change by two orders at magnitude (or more) during the first 9000

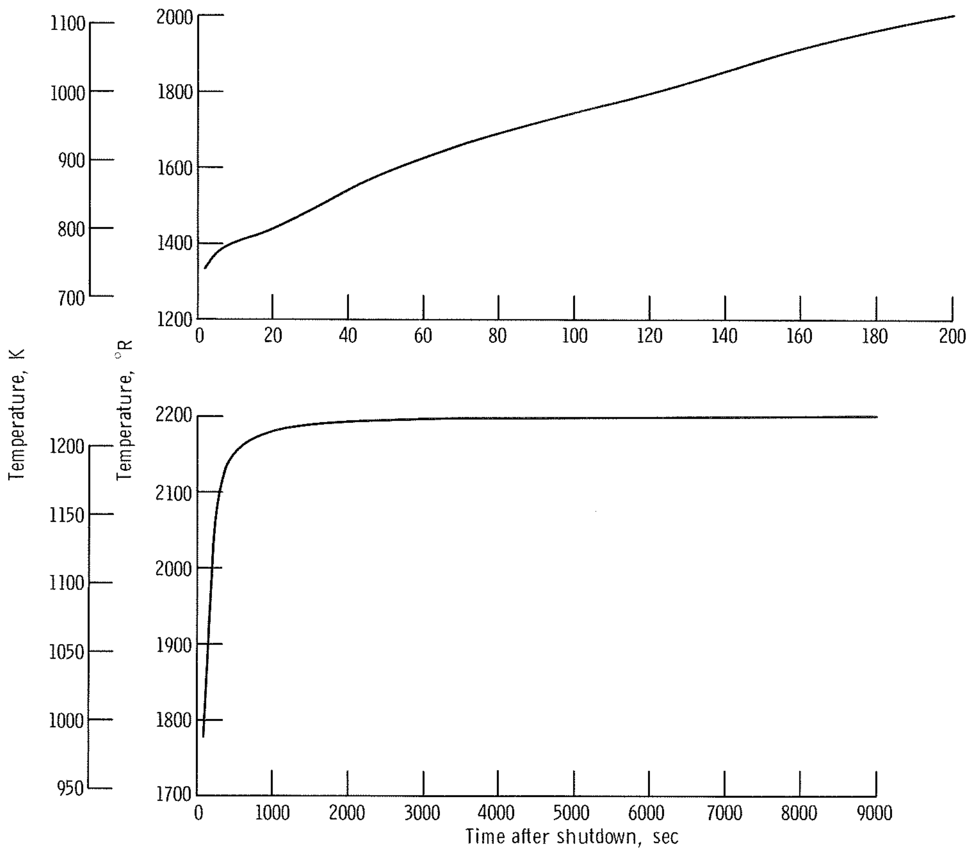

Figure 18. - Sodium temperature at auxiliary heat exchanger outlet against time after shutdown. Reactor operating time, 1 day; reactor power, 2.17 megawatts-thermal.

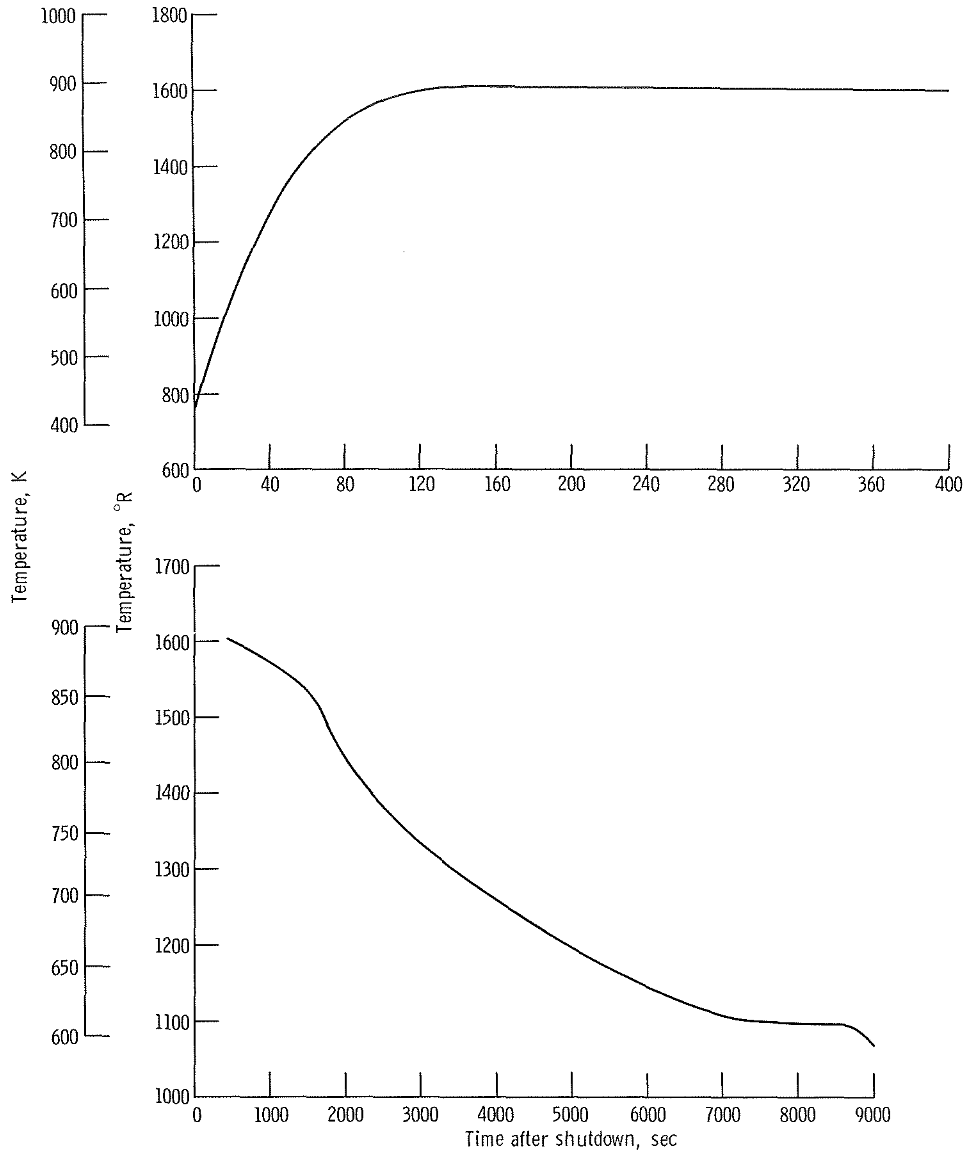

Figure 19. - Sodium temperature at auxiliary radiator outlet against time after shutdown. Reactor operating time, 1 day; reactor power, 2.17 megawatts-thermal.

seconds after shutdown. To properly regulate these flow rates over such a wide range may require a special flow control valve arrangement.

In the foregoing sections, we have shown how the flow rates and temperatures in the auxiliary loop vary with time after reactor shutdown. These calculated data are based on a specified set of operating conditions along with selected cross-sectional configurations for the auxiliary heat exchanger and auxiliary radiator. The required areas of the auxiliary heat exchanger and auxiliary radiator were determined to be relatively small. (The auxiliary heat exchanger surface area was determined to be 0.64 ft^2 or 0.0594 m^2; and the auxiliary radiator surface area was 37.7 ft^2 or 3.50 m^2.)

The reason that the auxiliary radiator is so small is due, in part, to the thermal capacitance of the auxiliary loop. Immediately following a shutdown, the decay heat generation rates (fig. 8) are relatively large. And the thermal capacitance of the auxiliary loop is used during the early part of the shutdown period (i.e., for about the first 60 sec or so) to absorb most of the decay heat.

SUMMARY OF RESULTS

An auxiliary radiator loop with sodium coolant was investigated as a possible means for removing decay heat from a proposed 2.17-megawatt-thermal space power reactor. The auxiliary loop considered for this study is made up of an auxiliary heat exchanger, an auxiliary radiator, a liquid-sodium pump, and the necessary flow control valves and piping. The sodium-cooled auxiliary loop is connected to the reactor primary loop by the auxiliary heat exchanger.

Based on a selected set of operating conditions and assumptions, minimum areas were determined for both the auxiliary heat exchanger and the auxiliary radiator.

The minimum auxiliary heat exchanger surface area required to transfer the decay heat from the reactor primary loop to the auxiliary loop was determined to be 0.64 square foot (0.0594 m^2). The auxiliary heat exchanger model used in this study is a simple counterflow type, consisting of two concentric cylindrical ducts.

The minimum surface area required by the auxiliary radiator was determined to be 37.7 square feet (3.50 m^2). Based on this surface area, the maximum radiator temperature was about 1760° R (978 K). The auxiliary radiator model consisted of 24 coplanar parallel tubes with central connecting fins of 100 percent effectiveness. The planform dimensions of the auxiliary radiator (assuming heat is rejected to space from both sides of the radiator) are: planform length, 6.0 feet (1.83 m); planform width, 3.14 feet (0.958 m).

The configurations and minimum areas for the auxiliary heat exchanger and auxiliary radiator were used to determine sodium flow rates and temperatures throughout the auxiliary loop as a function of time after reactor shutdown. The sodium flow rates and temperatures were determined for preshutdown reactor operating times of 1 year and 1 day.

The calculated data show that some of the sodium flow rates in the auxiliary loop change by two orders of magnitude (or more) during the first 9000 seconds after shutdown.

A significant conclusion obtained from this preliminary study is that the size (and/or mass) of the auxiliary loop is relatively small.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 26, 1970,
120-27.

APPENDIX - SYMBOLS

ΔA surface area of segment in analytical model of auxiliary radiator, ft^2; m^2

A_b surface area for heat transfer in auxiliary heat exchanger based on inside surface of sodium annular flow passage, ft^2; m^2

C_M specific heat of radiator material (tantalum), Btu/(lbm)(^oR); kW-sec/(kg)(K)

C_p specific heat, Btu/(lbm)(^oR); kW-sec/(kg)(K)

D_a inside diameter of lithium flow duct in auxiliary heat exchanger (see fig. 4), ft; m

D_b inside diameter of sodium annular flow passage in auxiliary heat exchanger (see fig. 4), ft; m

D_c outside diameter of sodium annular flow passage in auxiliary heat exchanger (see fig. 4), ft; m

E effectiveness of counterflow auxiliary heat exchanger (eq. (8))

h convective heat-transfer coefficient in auxiliary heat exchanger, Btu/(sec)(ft^2)(^oR); kW/(m^2)(K)

h_R convective heat-transfer coefficient in auxiliary radiator, Btu/(sec)(ft^2)(^oR); kW/(m^2)(K)

k_M thermal conductivity of auxiliary heat exchanger material (tantalum), Btu/(sec)(ft)(^oR); kW/(m)(K)

L_{Hx} length of auxiliary heat exchanger, ft; m

L_{Rad} length of auxiliary radiator, ft; m

ΔM mass of radiator segment in analytical model of auxiliary radiator, lbm; kg

Nu Nusselt number

Pe Peclet number

Pr Prandtl number

Q reactor decay heat generation rate, Btu/sec; kW

Re Reynolds number

T temperature, ^oR; K

$\overline{T}$ average coolant temperature in radiator segment, ^oR; K

$\overline{T}_R$ average material temperature of radiator segment, ^oR; K

t time after reactor shutdown, sec

U_b overall heat-transfer coefficient for auxiliary heat exchanger (eq. (3)), Btu/(sec)(ft^2)(^oR); kW/(m^2)(K)

$\dot{w}$ flow rate, lbm/sec; kg/sec

ϵ radiator surface emissivity

ρ density, lbm/ft^3; kg/m^3

σ Stefan-Boltzmann constant, 0.476×10^{-12} Btu/(sec)(ft^2)($^{\circ}$R^4); 5.71×10^{-11} kW/(m^2)(K^4)

$\Delta\tau$ auxiliary loop transport delay (eq. (15)), sec

Subscripts:

i inside surface of auxiliary radiator tubes (fig. 6)

in inlet of segment in analytical model of auxiliary radiator (fig. 6)

j segment number in analytical model of auxiliary radiator

Li lithium

Na sodium

o outside surface of auxiliary radiator tubes (fig. 6)

out outlet of segment in analytical model of auxiliary radiator (fig. 6)

s sink

1 reactor outlet (fig. 3)

2 reactor inlet (fig. 3)

3 auxiliary radiator bypass (fig. 3)

4 auxiliary radiator outlet (fig. 3)

5 auxiliary heat exchanger inlet (fig. 3)

6 auxiliary heat exchanger bypass (fig. 3)

7 auxiliary heat exchanger outlet (fig. 3)

8 auxiliary radiator inlet (fig. 3)

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